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INVESTIGATION OF A RAMJET USING BOUNDARY LAYER BLEED IN A TWO DIMENSIONAL SHORT CURVED WALL SUBSONIC DIFFUSER

MECHANICAL ENGINEERING DEPARTMENT
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This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public including foreign nations.

This technical report has been reviewed and is approved for publication.

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This report describes the bleeding requirements of a short contoured wall diffuser and the net performance gain of a ramjet equipped with such a high performance subsonic diffuser in terms of Thrust Coefficient and Range versus ramjet with conventional short diffuser. Analysis shows that at cruising Mach number of 2.5, the ramjet may gain 5% in Range and at take-over Mach number of 2.1, the ramjet may gain 6% in Thrust Coefficient. Comparison was also made with other types of high performance subsonic diffusers. In establishing the

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bleed requirements, detail information was included to show the methods of computing the boundary layer development along the curved wall and over the parallel walls. The latter is of three-dimensional nature which required a method using "cone-segment" simulation.

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I. SUMMARY

Diffusers for subsonic flow may be designed to achieve high recovery of kinetic energy in the form of pressure by use of slot suction and a proven analytical technique. This basic concept, known as the Griffith diffuser, has been thoroughly demonstrated for axially symmetric diffusers and briefly attemped with so-called two-dimensional diffusers. Herein a boundary layer analysis has been applied to a candidate design to determine the amount of sidewall bleed required for boundary layer control. The analysis predicts that about one percent of the entering flow, properly arranged, can insure attached flow.

Based on the total bleed requirement of the diffuser, a thrust analysis has been performed to determine the relative merits of the Griffith diffuser and a conventional short diffuser. The Griffith diffuser is expected to produce about 5% greater range at cruise and about 6% greater thrust at a take-over condition. These results are expected to hold or be surpassed in a more detailed system analysis having the capability of varying the vehicle afterbody to optimize thrust.

Based on the above prediction, it is recommended that a two-dimensional diffuser be tested to document the prediction of bleed requirement and performance.

II. INTRODUCTION

Short curved wall diffusers having contours designed by using an inverse solution of potential flow theory, have demonstrated high efficiency in converting fluid kinetic energy to static pressure [1][1]. The shortness in axial length and uniformity of exit velocity distribution of the diffuser are attractive for applications where these characteristics are essential. The inverse solution method [2] specifies the diffuser inlet, exit, and wall velocity distributions in a transformed plane, (ϕ-ψ) or velocity potential and stream function plane, without prior knowledge of the diffuser shape. The solution is in the form of a $\ln|q|$ distribution throughout the (ϕ-ψ) domain. Through a transformation the physical shape of the diffuser is readily determined.

For the potential flow theory to be accurate in the application of diffuser design, the boundary layer throughout the flow field must be kept thin. To fulfill this requirement, the wall velocity distribution is prescribed in three distinct regions, namely, an inlet wall region, an exit wall region and a slot region. Maintaining a constant or slightly accelerated velocity distribution in the first two regions insures a minimal layer growth. An abrupt deceleration takes place within the slot region to accomplish the change in wall velocity from a high value in inlet wall region to a low value in the exit wall region. Boundary layer control in the form of bleeding or suction in the slot region enables the remaining flow within the boundary layer to navigate the strong adverse pressure gradient.

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[1] Numbers in brackets are References at the end of the paper.

When the pressure level of the flow at the slot region is above the ambient, the boundary layer can be bled merely by providing an opening to the ambient. When the pressure level is below the ambient pressure energy must be provided to pump the fluid to ambient pressure. This type of contoured wall is similar in velocity distribution over the upper surface in shape to the high lift airfoil designed by A.A. Griffith [3]. To distinguish this type of curved short diffuser from other empirically derived curved wall diffusers, we refer to the curved short diffusers as Griffith diffusers. The amount of fluid which must be bled can be predicted by applying Taylor's criterion [4] which requires the fluid within the boundary layer to possess a minimum amount of kinetic energy (or velocity) to overcome an imposed pressure gradient. This requirement implies that the characteristics of the boundary layer of the flow entered and the local pressure jump determine the slot bleed rate. The pressure jump in this case reflects the diffuser area ratio. In certain flow systems, the flow enters the diffuser having a thin boundary layer, so the slot bleed rate would be low enough to be attractive in using such type of diffuser.

In a Griffith diffuser, the only pressure loss is due to friction. By the very nature of the diffuser it could be very short, therefore, even the skin friction would be a very minute amount. Experimental data [5] further suggest that the Griffith diffuser not only operates stably with a distorted flow distribution but also a disturbence at the inlet.

In bell shaped and annular diffusers, only the slot bleeding is to be concerned with, whereas in a two-dimensional diffuser, one needs to also consider the scheme of bleeding over the parallel walls. In such two-dimensional diffusers there exits a pair of parallel walls in addi-

tion to the pair of contoured walls. A three-dimensional boundary layer develops on this pair of parallel plane walls and is exposed to a range of pressure gradients. Near the region of the abrupt wall velocity change along the junction of the diverging curved wall and the parallel plane wall, the adverse pressure gradient is strong and the flow would separate from tne parallel walls provided there is no means of controlling the boundary layer. Away from the junction toward the center portion of the diffuser the boundary layer over the plane walls is subjected to a relatively milder adverse pressure gradient yet in most of the short diffusers it is sufficiently strong to require some degree of boundary layer control. Thus a distributed boundary layer bleed rate would be necessary to yield a total parallel wall bleed rate low enough for practical application. Up to now experiments conducted for two-dimensional diffusers used a uniform bleeding scheme for the parallel walls and the total bleed rate was generally much higher than desired 6].

In a ramjet application, high effectiveness of the subsonic diffuser is desired. Air within the subsonic diffuser has much higher pressure than the ambient which facilitates boundary layer bleeding, therefore the Griffith type diffuser presents itself to be a potential candidate for such an application.

The objective of this phase of investigation is to assess the merits of a two-dimensional Griffith type subsonic diffuser for ramjet applications when compared to a comparable short length straight wall diffuser. The selection of the two-dimensional diffuser is determined from ramjet technology rather than diffuser considerations. Generally a technology gain in a system element which, by itself, allows a range or thrust growth

is anticipated to result in a multiplied effect greater than its sole incorporation. This effect may usually be used to advantage by altering the overall design of the vehicle to allow best vehicle performance. Such activity is beyond the scope of the effort reported herein.

The effort described in the following first addresses the theoretical assessment of sidewall bleed flow rates required for the diffuser. In an ideal situation the suction rate is everywhere varied but in a practical system the ideal is approached by perhaps a two- or three-step permeability wall. The technology for such a wall is reasonably well advanced by using porous materials. Such technology is not expected to require a large cost increase because there are no special active controls or moving parts.

III. DIFFUSER DESIGN AND BOUNDARY LAYER ANALYSIS

Diffuser Contour

Using the Clemson University Potential Flow Inverse Solution Computer Program [5] to design two-dimensional contoured wall diffusers, one specifies the diffuser inlet and exit velocity distribution and the velocity distribution along the contoured walls. In this analytical investigation a symmetric diffuser was considered therefore only one contoured wall was involved. The design inputs specified were uniform, but not necessarily parallel flow upstream and parallel flow downstream. The velocity along the contoured wall gradually accelerated by 10% immediately upstream of the bleed slot and took a rapid drop to 0.4 of the inlet velocity across a narrow slot. Since the design input does not specify directly the area ratio and the exit height to centerline length, a trial and error procedure was used to yield a diffuser geometry having an area ratio of 2.5 and an exit height to centerline length ratio of 1.0.

Several computer runs were made. Among them, two were near the geometrical specification and were selected to be shown in Figures 1 and 2. From the computer output the location was selected where the streamlines are virtually parallel; this location was designated as diffuser inlet. The first design has an area ratio of 2.49 and exit to length ratio of 1.036 and the second has the ratios of 2.499 and 0.9. Either of the designs should be considered close enough to the specifications.

In the potential flow, thirty streamlines were used to represent one half of the symmetric 2-D flow field. Five of the thirty were streamlines making up the flow field of the suction slot. The remaining 25 streamlines constitute the entire flow field downstream of the suction slot and the greatest part of the field upstream of the suction slot.

In subsequent analysis the dimensions of the diffusers were:

Inlet Height	2 inches
Exit Height	4.98 inches and 4.998 inches
Centerline Length	5.159 inches and 4.498 inches

Boundary Layer Analysis

a. Slot Bleeding Requirement

In preparing the input for the potential flow inverse solution computer program, the slot bleeding rate must be specified. Additiona analysis is necessary to verify that the specified slot bleeding rate meets the Taylor criterion. Based on previous experience, a 3% slot bleed was assumed. Using the inverse solution and Herring and Mellor's program [7], a turbulent boundary layer analysis was performed having a one-seventh power law distribution, a displacement thickness of 0.002 ft, and a Reynolds number $\frac{U\delta^*}{\nu} = 1900$ as initial conditions along a two-dimensional contoured surface. From the output of the Herring amd Mellor program, the boundary layer profile immediately upstream of the slot was used to examine the adequacy of the 3% slot bleeding rate. The Taylor criterion states that $\frac{u_1}{U_1} = \sqrt{1 - (\frac{U_2}{U_1})^2}$ or $u_1 = 0.94\ U_1$ for present designs. The velocity terms used in Taylor's criterion are depicted in Figure 3.

The results of this analysis showed that the boundary layer immediately upstream the slot had a displacement thickness of 0.0008 ft and $u < 0.94\ U$ involved 1.44% of the flow. For both contoured walls a slot bleed of 2.88% of the entering flow is adequate to meet the Taylor's criterion. The computer output for the boundary layer development immediately upstream of the slot and the velocity profile of the second design are shown in Appendix I and Figure 11 respectively.

b. Parallel Wall Bleed Requirement

In the computation of parallel wall bleed requirement, every third of the thirty streamlines mentioned in potential flow inverse solution output were analyzed. Appropriate bleed rates were applied along each of the analyzed streamlines as a means of boundary layer control to prevent flow separation over the parallel walls.

The boundary layer development over the parallel walls is of three-dimensional nature. The spreading effect was approximated by considering each streamwise step of the boundary layer computation to be analogous to flow over a segment of a diverging cone. The equivalent cone segment geometry was established from the velocity distribution obtained from the potential flow inverse solution.

The boundary layer analysis thus performed was option #4 of the Herring and Mellor computer program. To initiate the boundary layer computation, a 0.002 ft. initial displacement thickness with a one-seventh power law profile for air at 1000°F and the maximum air velocity of 400 ft/sec were assumed. Option #4 of the program assumes that the boundary layer is turbulent. A displacement of 0.002 ft. is a reasonable estimate for a flow immediately downstream of a shock wave

stabilizing bleed system, and should result in turbulent flow.

Figure 4 shows a map of distribution of velocities normal to the parallel wall surface for the second diffuser design. Based on the map the total bleeding for two parallel walls was computed and it amounts to 0.7% of the through flow. The through flow was assumed to have an average velocity of 357 ft/sec at the diffuser inlet where the passage area is .0694 ft^2 (2 inches in height and 4.998 inches in width). In the vicinity of the slot (shaded area of Figure 4), owing to the high adverse pressure gradient, the bleed velocity requirement exceeded the limit of Herring and Mellor's analysis where good accuracy can be assured. The total bleed rate however, remains a good estimate because there is only a very limited area where the analysis is questionable. The computer printout which summarizes the boundary layer development of each analyzed streamline is presented as Appendix II. The slot bleed for controlling the flow along the curved walls amounts to approximately 3%. No corner effect at the junction between the curved walls and the sidewalls was considered in the analysis.

The second design is slightly shorter than the first design, thus having a smaller sidewall area. Streamlines of the second design, because of being shorter in length, are subjected to a stronger adverse pressure gradient; thus, higher bleed velocities would be required along some of the stream tubes. The overall sidewall bleed, however, should remain nearly the same for both designs.

Perhaps it is worthy to mention that the boundary layer development over the parallel walls was also analyzed by considering the boundary layer being two-dimensional. Two-dimensional analysis is a less accurate simulation than the cone-segment approach. The bleed distributions of

the two-dimensional boundary layer analysis are shown in Figures 5 and 6. The first design required 1.3% of the entering flow for total parallel wall bleed and the second design required 1.1%.

IV. RAMJET THRUST COEFFICIENT AND RANGE

The following air-cycle analysis was carried out for the purpose of examining the potential improvement in ramjet performance by using a Griffith subsonic diffuser which requires boundary layer bleeding. The effect of greater pressure is to allow greater thrust from the engine flow while the bleed flow diminishes net thrust due to its contribution to increased ram drag. The analysis is conducted to determine the net effect.

To present a quantitative discussion some of the operating and geometrical parameters were assigned with specific values. The analysis first computed thrust coefficient C_T vs. subsonic diffuser efficiency η_t (Total pressure at diffuser exit/Total pressure at diffuser inlet) with $\frac{M_i - M_b}{M_i}$ and $\frac{A_\infty}{A_3}$ as parameters. Here M_i represents the inlet flow, M_b is the bleed mass flow required for both shockwave stabilization and subsonic diffuser and A_∞/A_3 denotes the inlet area to combustor area ratio.

It was assumed that a bleed rate of 10% of the inlet flow is required to stabilize the shock location and 4% additional bleed is required to operate the Griffith type subsonic diffuser. Five values of A_∞/A_3 ranging from 0.25 to 0.30 were assumed, with combustion temperatures of 2400 R. This allowed C_T to approximate 0.25 which is the assumed vehicle drag coefficient.

Based on the calculations of C_T versus area ratio A_∞/A_3, the inlet size can be determined which allows $C_T = C_D = 0.25$. This can be done for both Griffith and conventional diffusers. The engine airflow for

both may be computed readily and the fuel flow is proportional to the engine air flow. The range is inversely proportional to the fuel flow allowing the vehicles with alternate diffusers to be easily compared by range alone.

The vehicles equipped with the alternative diffusers may then be operated at lower-than-cruise velocity to compare them at a take-over condition. An analysis of the net thrust coefficient at such a suppressed Mach number is presented.

In the discussion section, high performance diffusers of other types reported in the recent literature were also considered and compared with Griffith diffusers.

To allow the most fair comparison within a single analysis the following ground rules are met:

Isentropic supersonic inlet up to a normal shock at $M_x = 1.4$

A one dynamic head loss at the combustor dump

Combustion temperature 2400°R

Rayleigh line (constant area) combustion

Isentropic flow in the nozzle

Nozzle exit area = 0.9 of combustor area

The details of analysis are presented, followed by a discussion of the results obtained.

Analysis

Figure 7 depicts the ramjet with the relevant stations of the analysis designated.

For the purpose of comparing the performance of operation within the range of practical interest, the following were assumed.

a. Assumed operating conditions

$M_\infty = 2.5$

$T_{0,3} = (T_0)_{max} = 2400°R$ the first subscript 0 denotes stagnation condition

dumping from 2x to 2y

b. Assumed geometrical parameters

Two side mounted inlets

Subsonic diffuser area ratio $\frac{A_{2x}}{A_y} = 2.5$

$\frac{A_\infty}{A_3}$ took the values of 0.25, 0.26, 0.27, 0.28, and 0.30

$A_{2y} = A_3$

$A_e = .9\ A_3$

c. Inlet region

For comparative purposes only, an isentropic process was assumed up to the normal shock, then

$p_{0,x} = p_{0,\infty}$

The normal shock took place at $M_x = 1.4$, therefore

$p_{0,y} = .9582\ p_{0,\infty}$

d. Subsonic diffuser

From station y to station 2x, the flow is governed by the following equations:

(1) $p_{0,2x} = \eta_t \, p_{0,y}$

The values of η_t used in computation were 1.0, .975, .95, .925, .9, .85, .8, .75 and .70

(2) $(\rho AV)_{2x} = (\rho AV)_y$

(3) $\left(\frac{V^2}{2} + C_pT\right)_{2x} = \left(\frac{V^2}{2} + C_pT\right)_y$ with $C_p = .24$

(4) $p = \rho RT$ with $R = 53.35$

e. Dumping process

After the flow reaches station 2x, its Mach number is sufficiently low ($M_{2x} = 0.2$) that an incompressible flow approximation is acceptable. It was assumed in the computation the total pressure loss of this dumping process to be one dynamic head at station 2x.

$$p_{0,2y} = p_{0,2x} - \frac{\rho_{2x}}{2} V_{2x}^2$$

To satisfy the continuity requirement the following relation holds.

$$A_{2x}V_{2x} = A_{2y}V_{2y} \quad \cdot \quad \text{or } V_{2y} = V_{2x} \cdot \frac{A_{2x}}{A_{2y}}$$

The area ratio required for calculating V_{2y} was determined from the following equation

$$\frac{A_\infty}{A_3} = \left(\frac{A_\infty}{A_i^*}\right)_{M_\infty = 2.5} \left(\frac{A_i^*}{A_x}\right)_{M = 1.4} \frac{A_x}{A_y} \; \frac{A_y}{A_{2x}} \; \frac{A_{2x}}{A_{2y}} \; \frac{A_{2y}}{A_3}$$

$$(1)\left(\frac{1}{2.5}\right) \quad (1)$$

f. Combustor Flow

A Rayleigh line, constant flow area combustion process was assumed. The heat addition in non-dimensional form C_q was expressed as follows.

$$C_q = \frac{q}{\frac{a_\infty^2}{(\gamma - 1)g}\left(1 + \frac{\gamma - 1}{2} M_\infty^2\right)}$$

where $q = C_p\,(2400 - T_{0,\infty})$.

Here the constraint of maximum total temperature of 2400°R was imposed.

For computational convenience M*, the reference Mach number, and a*, the reference velocity of sound, were introduced where

$$\left(\frac{1}{\gamma - 1}\right) a^2 + \tfrac{1}{2}V^2 = \tfrac{1}{2}\left(\frac{\gamma + 1}{\gamma - 1}\right) a^{*2}$$

For $\gamma = 1.4$

$$M^{*2} = \frac{6}{1 + 5/M^2} \qquad \text{where } M^* = \frac{V}{a^*}$$

The energy continuity and momentum equations then take the following forms

$$(a_2^*)^2\,(1 + C_q) = a_3{}^{*2}$$

$$(\rho a^* M^*)_{2y} = (\rho a^* M^*)_3 \qquad A_{2y} = A_3$$

and $\rho_{2y}\, a_{2y}^{*2}\,(1 + M_2{}^{*2}) = \rho_3 a_3^{*2}\,(1 + M_3^{*2})$

Upon the completion of combustion

$$M^* = \frac{1 + M_2{}^{*2} - \sqrt{(1 - M_2{}^{*2})^2 - 4C_q\, M_2{}^{*2}}}{2M_2{}^{*}\sqrt{1 + C_q}}$$

The temperature and pressure ratio are:

$$T_3 = \frac{2400}{1 + \frac{\gamma - 1}{2} M_3^2}$$

$$\frac{p_3}{p_{2y}} = \sqrt{1 + C_q} \quad \frac{M_2^* \left(1 - \frac{\gamma - 1}{\gamma + 1} M_3^{*2}\right)}{M_3^* \left(1 - \frac{\gamma - 1}{\gamma + 1} M_2^{*2}\right)}$$

g. Nozzle flow

The flow through the converging-diverging nozzle was assumed to be isentropic. Using

$$\frac{A}{A_e^*} = \frac{1}{M} \left(\frac{1 + \frac{\gamma - 1}{2} M^2}{\frac{\gamma + 1}{2}} \right)^{\frac{\gamma + 1}{2(\gamma - 1)}}$$

the A_e^* was computed from the value of M_3. Knowing A^* in terms of A_3 and assume $A_e = .9A_3$, the above equation was used to compute M_e, the exit Mach number. The following equations were used for computing the exit velocity V_e and exit pressure p_e:

$$V_e = 49.01\, M_e \left(\frac{2400}{1 + \frac{\gamma - 1}{2} M_e^2} \right)^{\frac{1}{2}}$$

$$p_e = p_3 \frac{\left(1 + \frac{\gamma - 1}{2} M_3^2\right)^{\frac{\gamma}{\gamma - 1}}}{\left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{\frac{\gamma}{\gamma - 1}}}$$

h. Thrust coefficient

Define the thrust coefficient C_T as following

$$C_T = \frac{\text{Thrust}}{\frac{\rho_\infty}{2} V_\infty^2 A_3}$$

The thrust was computed as following

$$\text{Thrust} = (M_i - M_b) V_e - M_i V_\infty + (p_e - p_\infty) A_e$$
$$= M_i V_e - M_i V_\infty + (p_e - p_\infty) A_e - M_b V_e$$

The last term $M_b V_e$ is the ram drag associated with bleeding.

$$C_T = 2 \frac{\rho_3 V_3}{\rho_\infty V_\infty} \frac{V_e}{V_\infty} - \frac{M_i}{M_i - M_b} + 2 \frac{(p_e - p_\infty)}{\rho_\infty V_\infty^2} \cdot \frac{A_e}{A_3}$$

<u>Results and Discussion</u>

Figure 8 shows C_T vs η_t for $T_{0,3}$ = 2400°R, p_∞ = 14.7 psia, M_∞ = 2.5 with $\frac{M_i - M_b}{M_i}$ and $\frac{A_\infty}{A_3}$ as parameters. Figure 9 is a similar plot for $M_\infty = 2.1$ $\frac{A_\infty}{A_3} = .28$ and .30 with $\frac{M_i - M_b}{M_i} = .9$ and .86.

Figure 8 was prepared about $C_T = .25$ to examine the potential gain of missile range when the Griffith type diffuser is used. Figure 9 may be used to examine the potential gain in C_T at take-over operation.

a. Range

Assume a ramjet cruising at $M_\infty = 2.5$ requires that $C_T = .25$. Further assume (1) a normal shock at the inlet of a short straight wall subsonic diffuser would require 10% bleeding [8] to stabilize the shockwave location and (2) the Griffith subsonic diffuser requires 4% additional bleeding downstream of shockwave bleeding to yield a value η_t of 0.98 [5] for the subsonic diffuser. On Figure 8, a point is designated "Conventional Diffuser" for the ramjet with conventional diffuser (η_t = 0.75).

Such a design needs an area ratio (which reflects the mass flow) $\frac{A_\infty}{A_3}$ of 0.27 and $\frac{M_i - M_b}{M_i} = 0.9$ to produce a C_T value of 0.25. A C_T of 0.25 also can be produced by a ramjet having the Griffith type diffuser of the same area ratio and $\frac{M_i - M_b}{M_i} = 0.86$. Such a point is designated "Griffith Diffuser" on Figure 8. The range ratio of these two ramjets is the inverse of the ratio of air flow being heated for those ramjets, since the heat addition per unit mass is constant. Therefore

$$\frac{\text{Range}_{\text{Griffith Diffuser Ramjet}}}{\text{Range}_{\text{Conventional Diffuser Ramjet}}} = \frac{\left[\frac{M_i - M_b}{M_i} \; \frac{A_\infty}{A_3} \; \rho_\infty A_3 V_\infty\right]_{\text{conventional diffuser}}}{\left[\frac{M_i - M_b}{M_i} \; \frac{A_\infty}{A_3} \; \rho_\infty A_3 V_\infty\right]_{\text{Griffith Diffuser}}}$$

or there is a potential gain of 4.6% in range.

b. Take-over Thrust Coefficient

Assume take-over Mach number to be 2.1, and two ramjet geometries both have a shock wave at a M_x value of 1.4. The C_T values for both ramjets can be readily obtained. Figure 9 shows that at $\eta_t = .75$ and $\frac{M_i - M_b}{M_i} = 0.9$, that is, for a ramjet with conventional diffuser, the C_T value is .244. At $\eta_t = .98$ and $\frac{M_i - M_b}{M_i} = .086$, that is, a ramjet with Griffith diffuser one may have C_T value of .259 or a gain in C_T of 6.1%. The growth in excess thrust is anticipated to greatly favor the Griffith diffuser.

Comparison with Other High Performance Diffusers

In each case which follows, based on an early NASA Langley study, we assessed that 10% bleed was necessary to stabilize the shock location. This bleed also provides a thin boundary layer to the subsonic diffuser which follows immediately downstream of the normal shock [8].

The total pressure ratio of a two-dimensional Griffith diffuser of area ratio 2.5, length to exit width ratio of approximately one is estimated based on test data as $\eta_t = 0.98$, requiring an additional four percent bleed as diffuser suction. Incompressible test data for Griffith diffusers of circular cross section, annular cross section, and a two-dimensional diffuser (slot bleeding requirement alone for two-dimensional diffuser [6]) have shown that one can accurately predict the bleed requirement. The method of bleed prediction involves boundary layer growth calculation and use of Taylor's criterion. These calculations are simple and well understood; therefore, one is reasonably confident of the extrapolation of test data to operation in the compressible flow regime.

The diffusers of Cranfield institute of Technology reported by Adkins [9], and NASA Lewis diffusers reported by Povinelli [10] are considered as high performance diffusers. It is very difficult to extrapolate with certainty the incompressible test data to high subsonic Mach number operation for Adkins' work. The primary difficulty is that the mechanics of controlling a pressure field by using trapped vortices is less understood than are simple boundary layer effects. In the case of NASA Lewis diffusers (Stratford and dm/dz diffusers), the tested diffusers were several times longer ($\frac{L}{\Delta R}$ = 12, 6 where ΔR is the width of

the annular passage at diffuser exit) than Griffith diffusers and Cranfield diffusers. The η_t values of Stratford and dm/dz type diffusers with $\frac{L}{\Delta R} < 2$ are therefore difficult to estimate. Short, annular dump diffusers with area ratios of four to one when tested up to inlet Mach numbers of 0.27 and with bleed of 13.5% have achieved diffuser effectiveness of 70% as reported by Juhasz of NASA LRC [11]. The incompressible data translates to a total pressure ratio η_t of 0.75 approximately. This performance indicates that a short diffuser's effectiveness could be degenerated rapidly if the suction is applied without additional means of control the pressure distribution. The Juhasz test data and data of Reference 12 form the basis of assuming $\eta_t = .75$ for conventional short diffusers without suction. This also agrees with diffuser performance data as reported in the Bulletin of the Japanese Society of Mechanical Engineering, Reference 13, indicating that a short two-dimensional diffuser with angles of expansion up to 90° and area ratios of four to one with 3 to 4% suction were able to achieve a maximum diffuser efficiency of 70%. This incompressible test data translates to an η_t value of 0.76. The above discussion was summarized in Figure 10 which is reproduced from Figure 8 with the estimated zones of performance of several types of diffusers added to it. The performance of comparably short diffusers has been estimated by diminishing the performance reported for the long diffusers in accordance with experience. This graph should be viewed as merely an educated guess.

V. CONCLUSION

Herein an attempt has been made to compare the estimate performance of vehicles equipped with conventional and unconventional diffusers where minimum diffuser length is a requirement. The benefit of increased pressure is offset by the detriment of the ram drag of any necessary bleed air. The use of the Griffith diffuser is estimated to afford an increase of about 5% in cruise range at M = 2.5. At an assumed take-over condition of M = 2.1, its use results in a 6% thrust advantage over a conventional diffuser. Neither of these results has made use of modifications to the vehicle (base and boattail drag) which should further enhance the advantage of the advanced diffuser. The 4% bleed requirement includes 1% for parallel wall bleed which is an analytical prediction and remains to be verified experimentally.

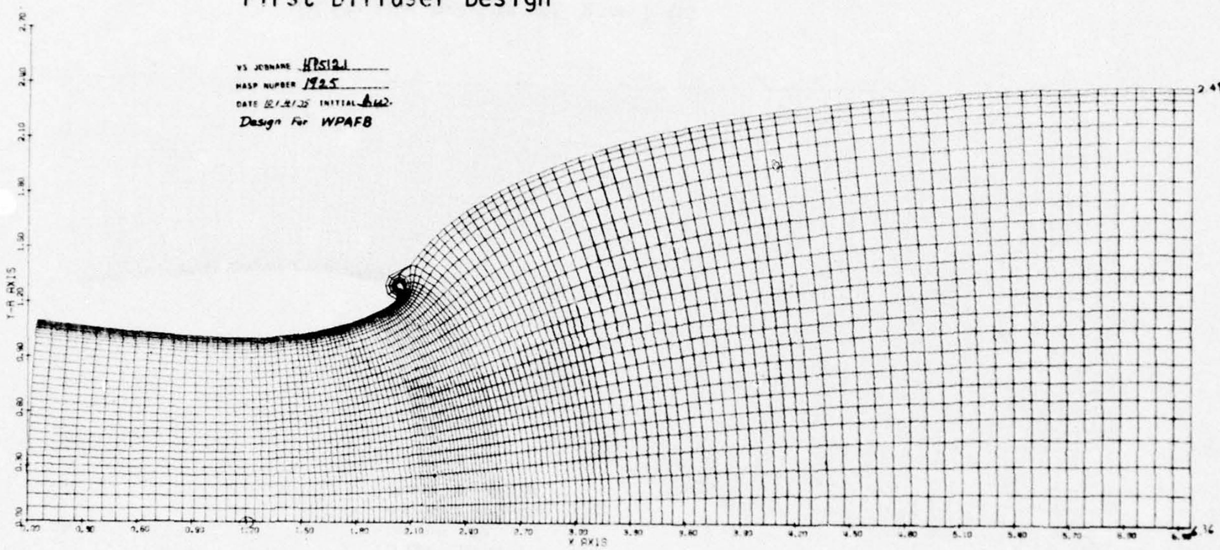
The relative comparison between Griffith and other advanced concepts favors the Griffith diffuser. However, the comparison is based on extrapolation of low velocity data for some or represents correction for the effect of a constant area diffuser extension for others. Therefore, the comparison must be understood as being relatively uncertain.

VI. RECOMMENDATIONS

1. An experimental investigation to verify the bleed requirement of the parallel wall is necessary. It is essential that a simple bleed scheme should be developed.

2. An experimental investigation should be conducted to examine the possibliity of replacing a major part of contoured diffuser wall surface by segments of plane surfaces to reduce the cost of fabrication. The effect of bleed requirements due to contour modification should also be examined experimentally.

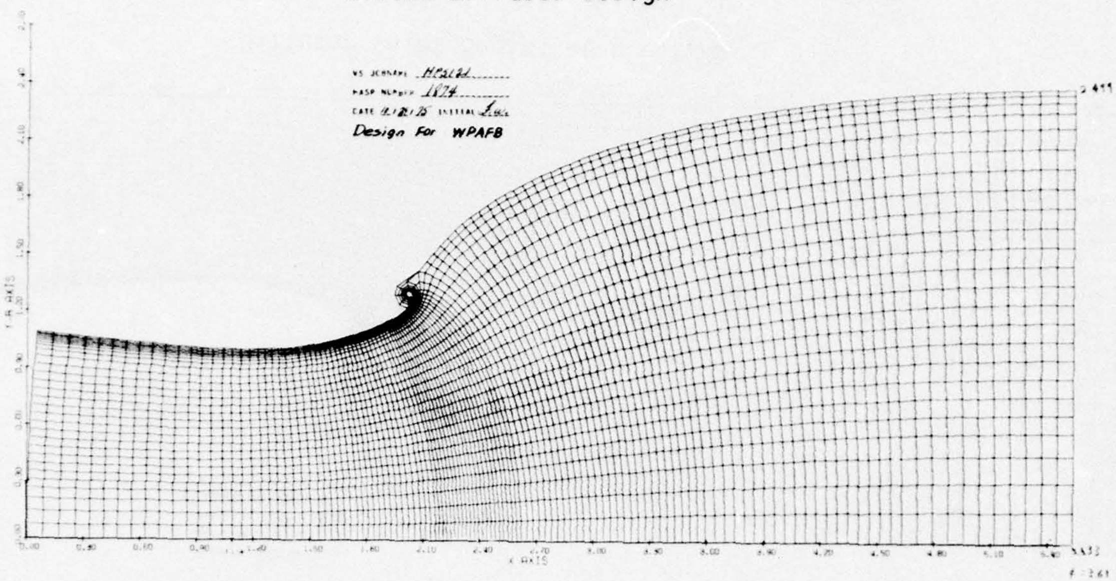
First Diffuser Design



Diffuser inlet begins at x = 1.20

FIGURE 1. DIFFUSER GEOMETRY OBTAINED BY USING INVERSE DESIGN METHOD

Second Diffuser Design



Diffuser begins at x = 1.04

FIGURE 2. DIFFUSER GEOMETRY OBTAINED BY USING INVERSE DESIGN METHOD

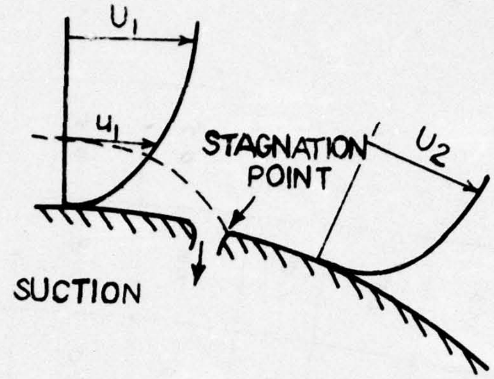


FIGURE 3. VELOCITY DESIGNATIONS IN TAYLOR'S CRITERION.

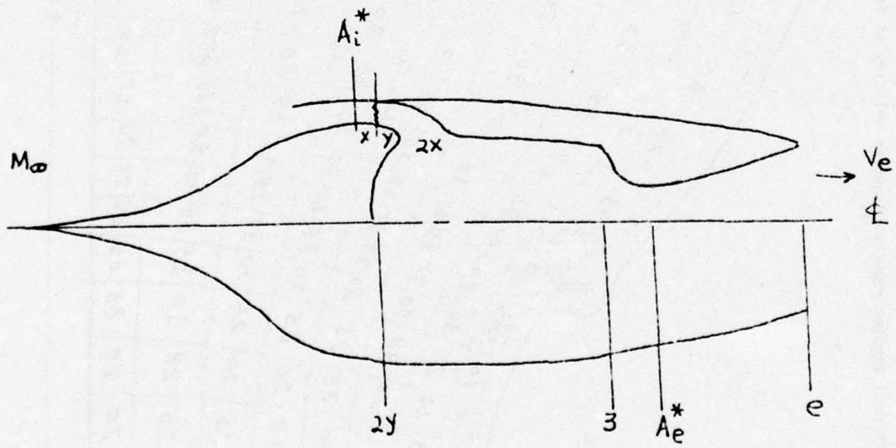


FIGURE 7. STATION DESIGNATION OF A RAMJET.

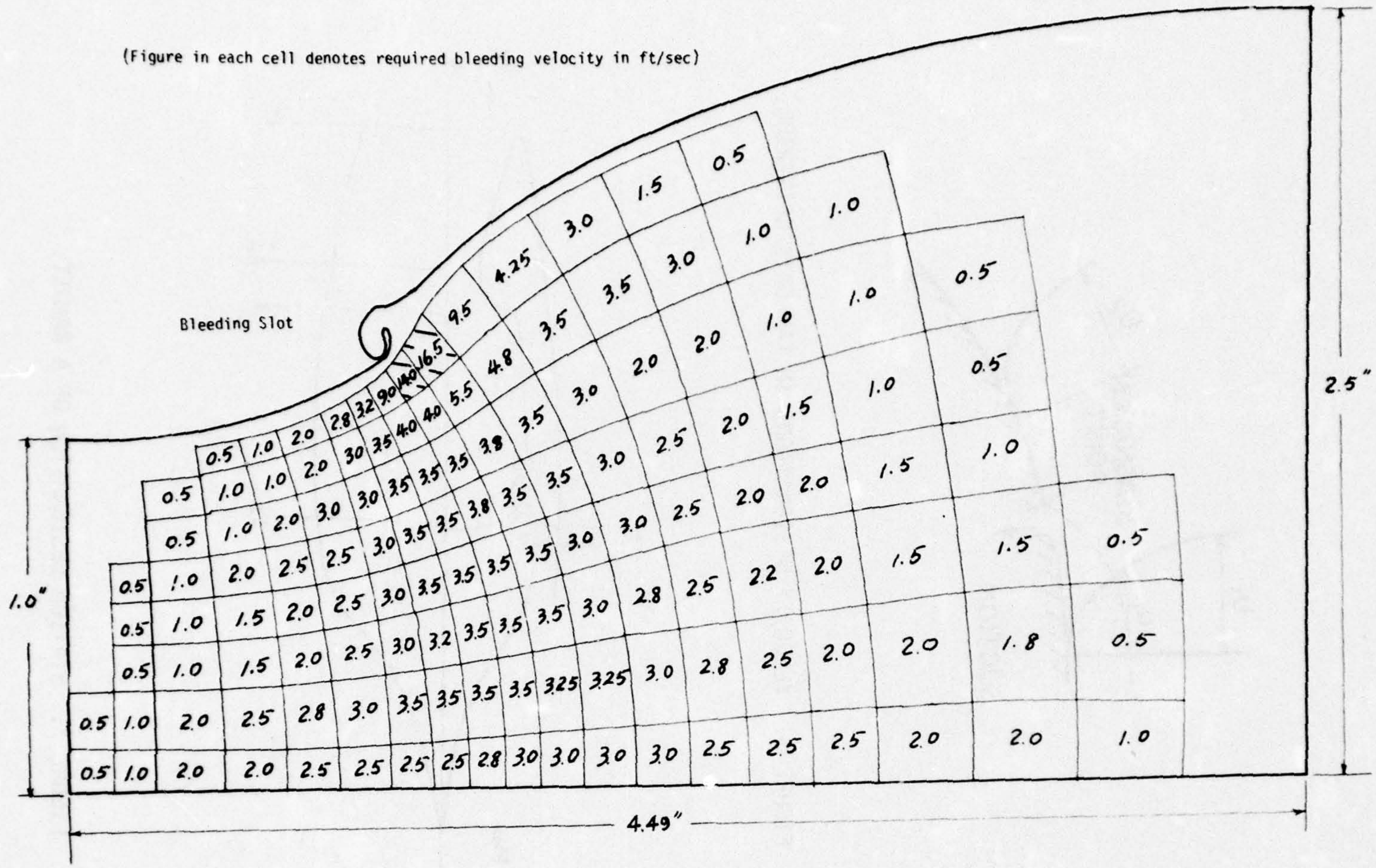


FIGURE 4. BLEED VELOCITY DISTRIBUTION MAP, SECOND DESIGN SIMULATED CONE-SEGMENT BOUNDARY LAYER COMPUTATION

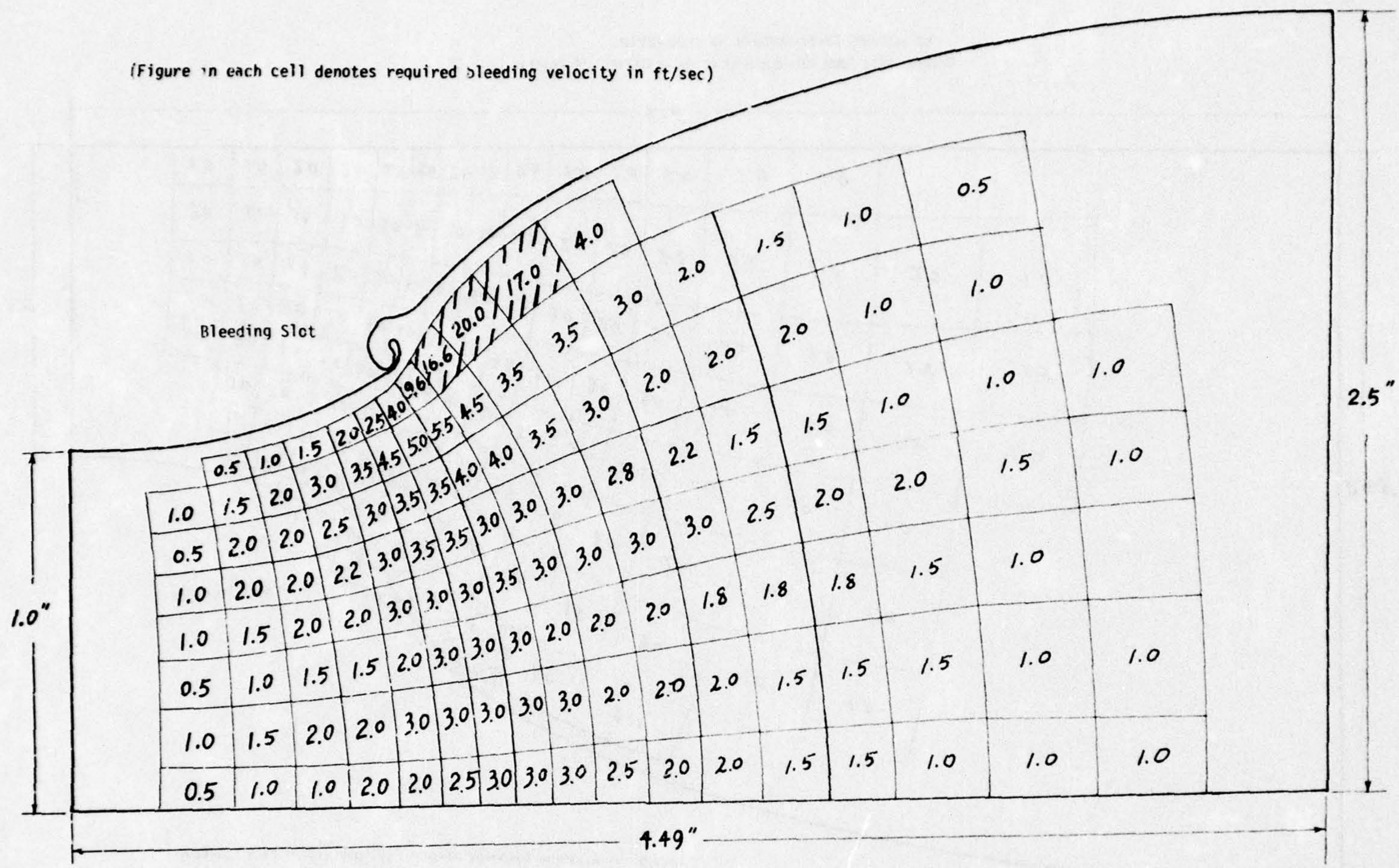


FIGURE 5. BLEED VELOCITY DISTRIBUTION MAP, SECOND DESIGN TWO-DIMENSIONAL BOUNDARY LAYER COMPUTATION

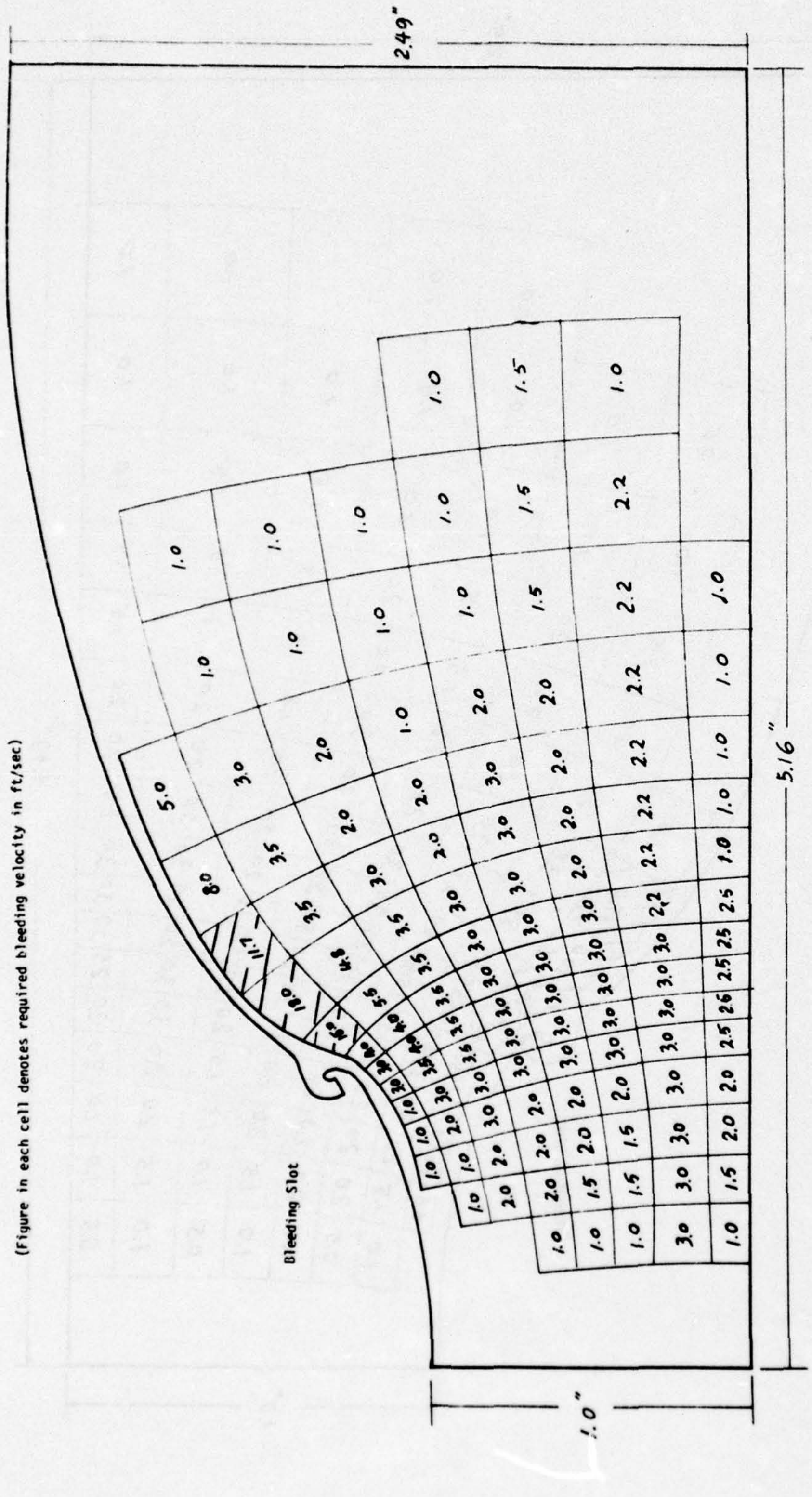


FIGURE 6. BLEED VELOCITY DISTRIBUTION MAP, FIRST DESIGN TWO-DIMENSIONAL BOUNDARY LAYER COMPUTATION

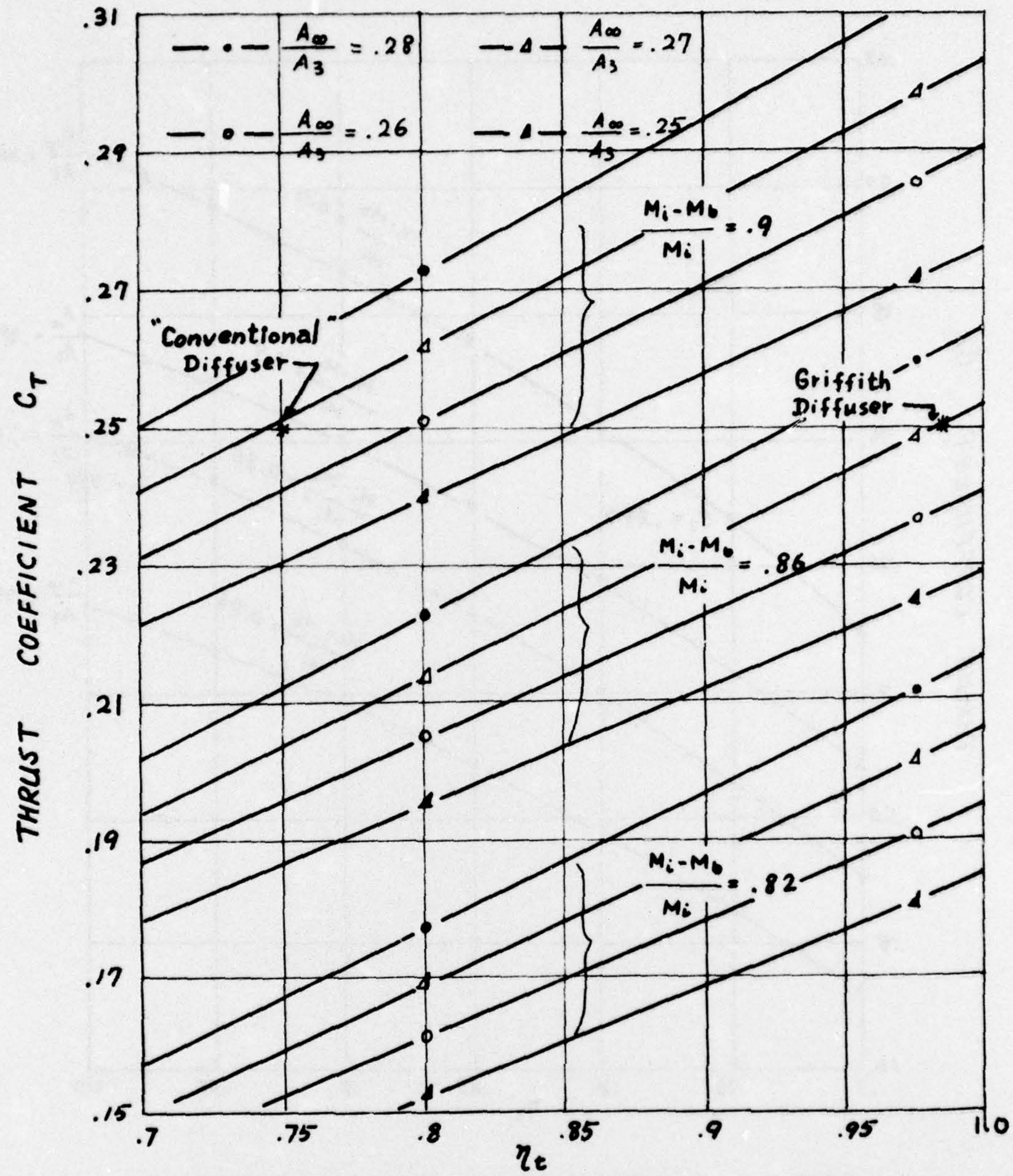


FIGURE 8. THRUST COEFFICIENT C_T VS DIFFUSER TOTAL PRESSURE RATIO η_t

$M_\infty = 2.5$

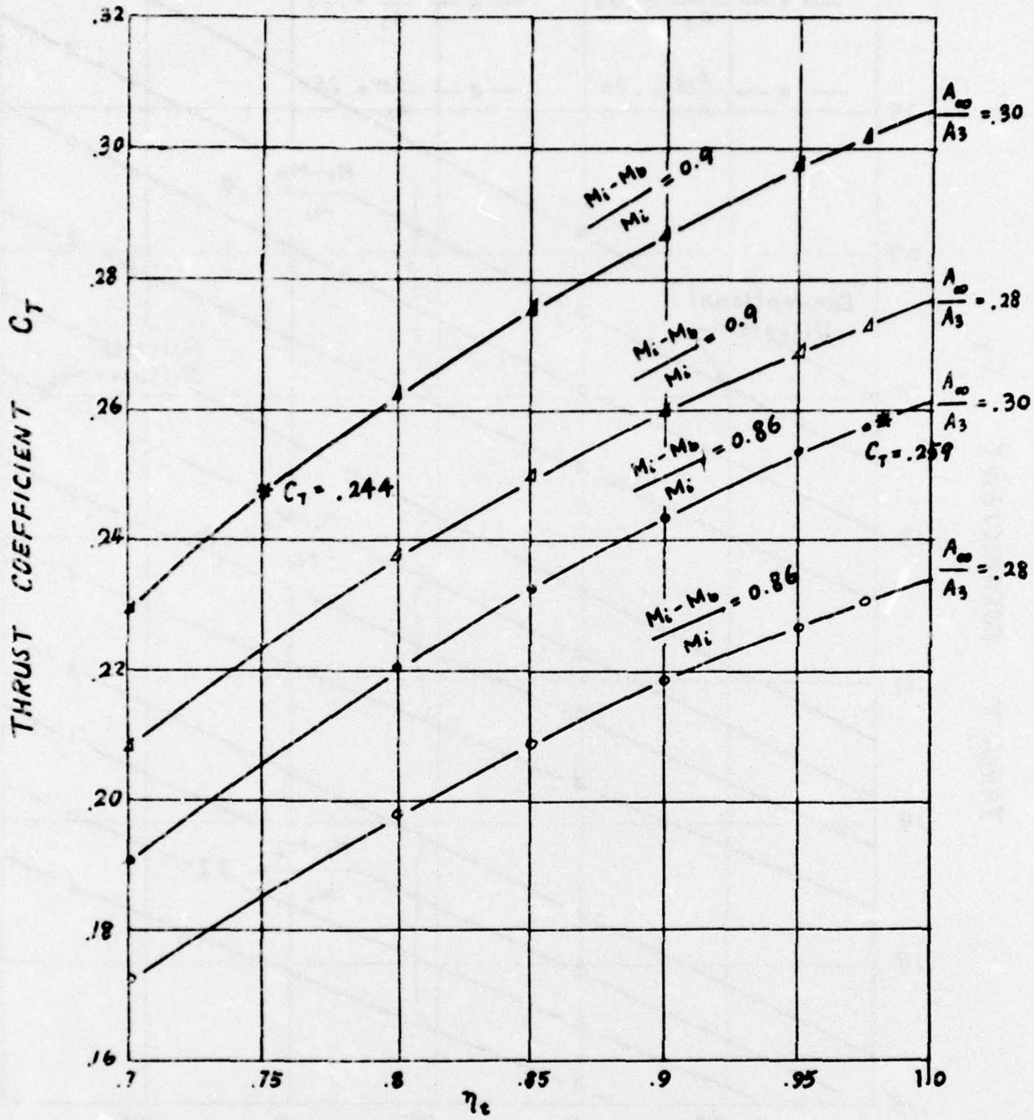


FIGURE 9. THRUST COEFFICIENT C_T VS DIFFUSER TOTAL PRESSURE RATIO η_t

M_∞ 2.1

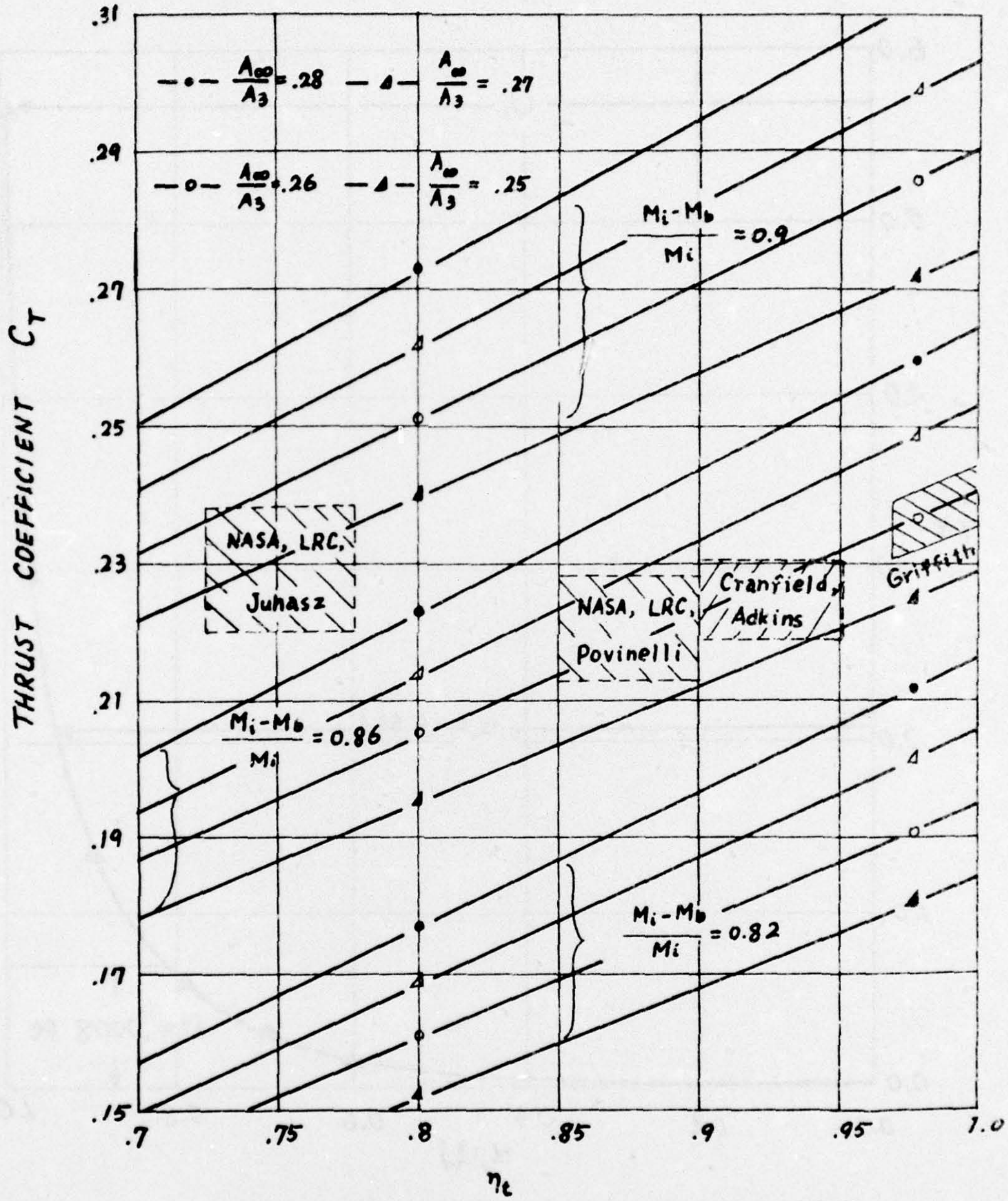


FIGURE 10. ESTIMATED ZONES OF PERFORMANCE OF SHORT DIFFUSERS

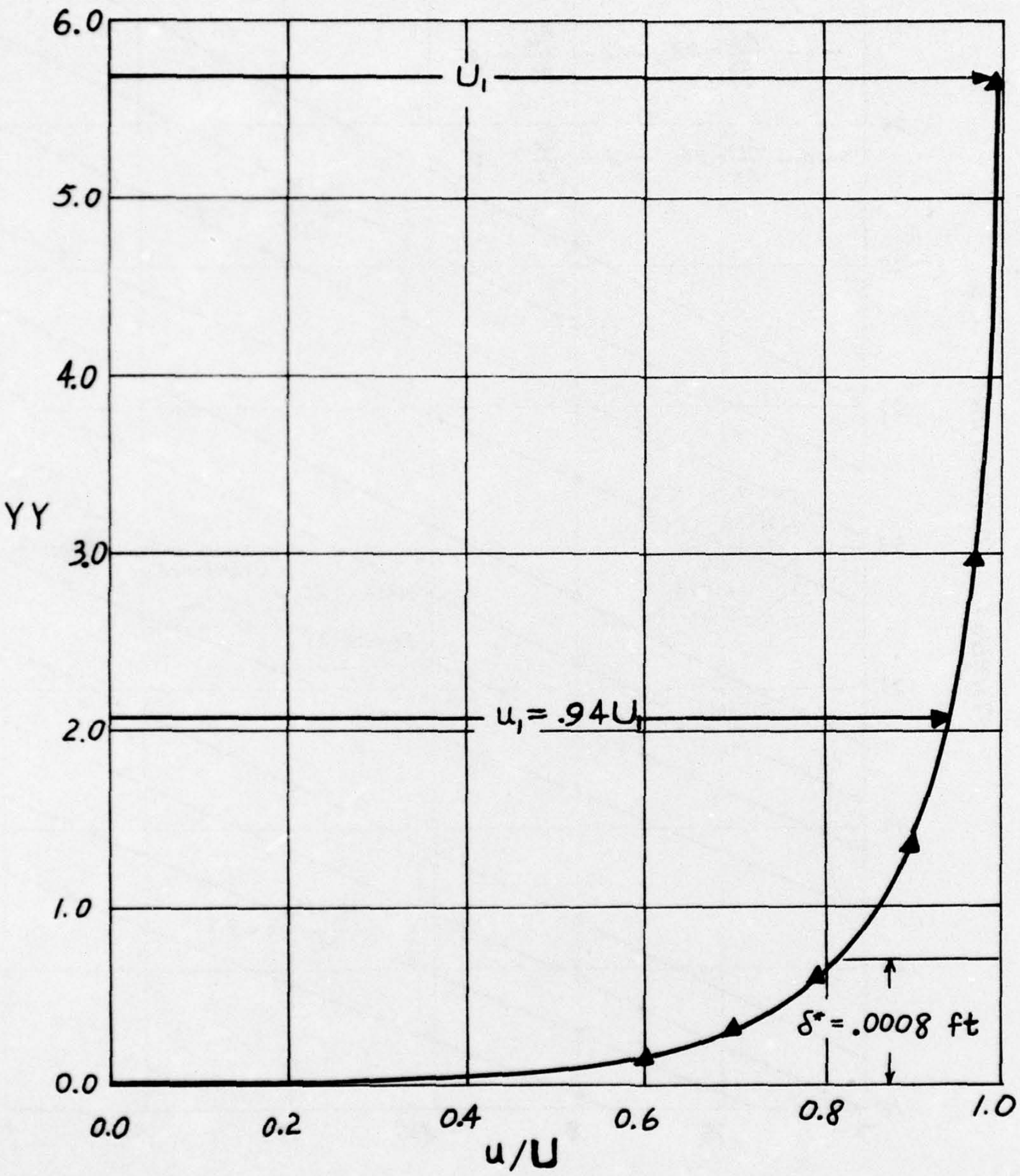


FIGURE 11. VELOCITY PROFILE IMMEDIATE UPSTREAM OF BLEED SLOT.

FLUID WITH $u_1 < 0.94\ U_1$ MUST BE REMOVED.

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APPENDIX I

PRINCIPAL BOUNDARY LAYER PARAMETERS FOR
STREAMLINE NC. 30 FOR THE DEVELOPEMENT OF BOUNDARY

X	DT	MT	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2975	0.003227	1980.	396.0000	1.000	0.0	0.0	0.0	0.0
0.0268	0.0013	0.0009	1.4177	0.004924	1282.	398.0000	1.000	0.0	0.0	0.0	0.0
0.0690	0.0014	0.0010	1.3956	0.004784	1351.	400.0000	1.000	0.0	0.0	0.0	0.0
0.0826	0.0014	0.0010	1.4097	0.004617	1440.	400.0000	1.000	0.0	0.0	0.0	0.0
0.1035	0.0015	0.0011	1.4198	0.004607	1518.	400.0000	1.000	0.0	0.0	0.0	0.0
0.1226	0.0016	0.0011	1.4196	0.004870	1584.	400.0000	1.000	0.0	0.0	0.0	0.0
0.1355	0.0014	0.0010	1.4040	0.005518	1485.	414.3999	1.000	0.0	0.0	0.0	0.0
0.1469	0.0012	0.0009	1.3903	0.005957	1336.	437.5999	1.000	0.0	0.0	0.0	0.0
0.1576	0.0010	0.0007	1.3928	0.006482	1208.	465.0000	1.000	0.0	0.0	0.0	0.0
0.1676	0.0009	0.0006	1.3890	0.009243	1083.	500.0000	1.000	0.0	0.0	0.0	0.0
0.1691	0.0008	0.0006	1.3872	0.007754	996.	520.0000	1.000	0.0	0.0	0.0	0.0

APPENDIX II

PRINCIPAL BOUNDARY LAYER PARAMETERS FOR
STREAMLINE NO. 0 BOUNDARY DESIGN WITH SUC

X	DT	HT	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2939	0.003823	1671.	334.2000	1.000	0.1536	-0.500000	0.0	0.0
0.0480	0.0013	0.0009	1.3948	0.006887	1059.	331.5999	1.000	0.1542	-1.000000	0.0	0.0
0.0890	0.0012	0.0010	1.3060	0.009114	1011.	324.0000	1.000	0.1560	-2.000000	0.0	0.0
0.1230	0.0013	0.0010	1.3024	0.010124	1019.	313.5999	1.000	0.1585	-2.000000	0.0	0.0
0.1530	0.0014	0.0010	1.3001	0.011106	1027.	302.0000	1.000	0.1616	-2.500000	0.0	0.0
0.1820	0.0014	0.0011	1.2956	0.012375	1034.	289.2000	1.000	0.1651	-2.500000	0.0	0.0
0.2100	0.0015	0.0012	1.3084	0.011831	1066.	275.5999	1.000	0.1691	-2.500000	0.0	0.0
0.2300	0.0017	0.0013	1.3101	0.012616	1097.	264.0000	1.000	0.1728	-2.500000	0.0	0.0
0.2500	0.0018	0.0013	1.3216	0.013418	1122.	254.0000	1.000	0.1762	-2.799999	0.0	0.0
0.2700	0.0018	0.0014	1.3224	0.015630	1130.	244.4000	1.000	0.1796	-3.000000	0.0	0.0
0.2910	0.0019	0.0015	1.3218	0.015890	1133.	235.2000	1.000	0.1830	-3.000000	0.0	0.0
0.3180	0.0020	0.0015	1.3225	0.017137	1128.	224.8000	1.000	0.1873	-3.000000	0.0	0.0
0.3490	0.0021	0.0016	1.3236	0.017585	1123.	213.6000	1.000	0.1921	-3.000000	0.0	0.0
0.3820	0.0022	0.0017	1.3309	0.016089	1128.	202.8000	1.000	0.1971	-2.500000	0.0	0.0
0.4200	0.0023	0.0017	1.3409	0.015850	1129.	192.4000	1.000	0.2024	-2.500000	0.0	0.0
0.4750	0.0024	0.0018	1.3403	0.017863	1073.	182.0000	1.000	0.2081	-2.500000	0.0	0.0
0.5330	0.0024	0.0018	1.3300	0.015397	1027.	171.6000	1.000	0.2143	-2.000000	0.0	0.0
0.5950	0.0024	0.0018	1.3311	0.016366	982.	163.2000	1.000	0.2198	-2.000000	0.0	0.0
0.6710	0.0023	0.0017	1.3295	0.016107	898.	156.8000	1.000	0.2242	-1.799999	0.0	0.0
0.7590	0.0022	0.0016	1.3206	0.014853	815.	151.2000	1.000	0.2283	-1.500000	0.0	0.0
0.8490	0.0021	0.0016	1.3271	0.010896	767.	147.6000	1.000	0.2311	-1.000000	0.0	0.0
0.9410	0.0022	0.0016	1.3730	0.007880	799.	145.2000	1.000	0.2330	-0.500000	0.0	0.0

PRINCIPAL BOUNDARY LAYER PARAMETERS FOR
ATREAMLINE NO. 3 BOUNDARY DESIGN WITH SUC

X	DT	MT	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2939	0.005414	1180.	336.0000	1.000	0.1530	-0.500000	0.0	0.0
0.0480	0.0013	0.0009	1.4290	0.007412	786.	333.5999	1.000	0.1537	-1.000000	0.0	0.0
0.0890	0.0014	0.0010	1.3750	0.009039	775.	326.3999	1.000	0.1554	-2.000000	0.0	0.0
0.1223	0.0014	0.0010	1.3570	0.010328	775.	316.3999	1.000	0.1578	-2.000000	0.0	0.0
0.1515	0.0015	0.0011	1.3560	0.010759	788.	304.3999	1.000	0.1609	-2.500000	0.0	0.0
0.1800	0.0015	0.0011	1.3530	0.012929	790.	291.5999	1.000	0.1644	-2.799999	0.0	0.0
0.2080	0.0016	0.0012	1.3427	0.013538	787.	278.0000	1.000	0.1684	-3.000000	0.0	0.0
0.2275	0.0017	0.0013	1.3381	0.016247	793.	266.0000	1.000	0.1721	-3.500000	0.0	0.0
0.2465	0.0013	0.0013	1.3401	0.017203	791.	256.0000	1.000	0.1755	-3.500000	0.0	0.0
0.2570	0.0018	0.0014	1.3373	0.017958	788.	245.6000	1.000	0.1791	-3.500000	0.0	0.0
0.2880	0.0019	0.0014	1.3383	0.018701	788.	235.2000	1.000	0.1830	-3.500000	0.0	0.0
0.3140	0.0020	0.0015	1.3438	0.018456	782.	224.8000	1.000	0.1872	-3.250000	0.0	0.0
0.3455	0.0021	0.0015	1.3442	0.019087	772.	212.8000	1.000	0.1925	-3.250000	0.0	0.0
0.3785	0.0021	0.0016	1.3465	0.019088	761.	201.6000	1.000	0.1977	-3.000000	0.0	0.0
0.4175	0.0022	0.0016	1.3501	0.018691	741.	191.2000	1.000	0.2030	-2.799999	0.0	0.0
0.4780	0.0022	0.0016	1.3488	0.018514	690.	180.0000	1.000	0.2092	-2.500000	0.0	0.0
0.5300	0.0022	0.0017	1.3443	0.016027	668.	170.0000	1.000	0.2153	-2.000000	0.0	0.0
0.5930	0.0023	0.0017	1.3619	0.015294	647.	162.0000	1.000	0.2206	-1.799999	0.0	0.0
0.6660	0.0022	0.0016	1.3733	0.013959	611.	156.0000	1.000	0.2248	-1.500000	0.0	0.0
0.7530	0.0023	0.0016	1.3915	0.010730	598.	150.4000	1.000	0.2289	-1.000000	0.0	0.0
0.8030	0.0025	0.0017	1.4338	0.007785	637.	146.8000	1.000	0.2317	-0.500000	0.0	0.0
0.8730	0.0028	0.0019	1.4785	0.005296	719.	144.4000	1.000	0.2336	0.0	0.0	0.0

PRINCIPAL BOUNCARY LAYER PARAMETERS FOR
STREAMLINE NC. 6 BOUNDARY CESIGN WITH SUC

X	DT	MI	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2975	0.003789	1686.	337.2000	1.000	0.1529	-0.500000	0.0	0.0
0.0410	0.0013	0.0009	1.4048	0.006726	1095.	331.2000	1.000	0.1542	-1.000000	0.0	0.0
0.0740	0.0014	0.0010	1.3568	0.007730	1110.	321.5999	1.000	0.1565	-1.500000	0.0	0.0
0.1320	0.0014	0.0011	1.3314	0.009309	1089.	310.0000	1.000	0.1594	-2.000000	0.0	0.0
0.1600	0.0015	0.0011	1.3278	0.010949	1105.	297.2000	1.000	0.1628	-2.500000	0.0	0.0
0.1370	0.0016	0.0012	1.3320	0.012605	1115.	283.2000	1.000	0.1668	-3.000000	0.0	0.0
0.2060	0.0017	0.0013	1.3326	0.014119	1136.	270.0000	1.000	0.1708	-3.200000	0.0	0.0
0.2260	0.0018	0.0013	1.3397	0.015547	1139.	258.7998	1.000	0.1745	-3.500000	0.0	0.0
0.2460	0.0018	0.0014	1.3370	0.016790	1132.	247.6000	1.000	0.1784	-3.500000	0.0	0.0
0.2670	0.0019	0.0014	1.3393	0.017150	1130.	236.4000	1.000	0.1826	-3.500000	0.0	0.0
0.2940	0.0020	0.0015	1.3477	0.015998	1125.	224.4000	1.000	0.1874	-3.000000	0.0	0.0
0.3250	0.0021	0.0016	1.3564	0.015121	1132.	212.0000	1.000	0.1919	-2.799999	0.0	0.0
0.3580	0.0023	0.0017	1.3675	0.014545	1135.	200.0000	1.000	0.1985	-2.500000	0.0	0.0
0.3970	0.0024	0.0018	1.3761	0.013301	1140.	188.0000	1.000	0.2048	-2.200000	0.0	0.0
0.4540	0.0025	0.0018	1.3775	0.013494	1098.	177.2000	1.000	0.2109	-2.000000	0.0	0.0
0.5140	0.0026	0.0019	1.3723	0.011229	1071.	167.2000	1.000	0.2171	-1.500000	0.0	0.0
0.5760	0.0026	0.0019	1.3590	0.013165	1039.	159.6000	1.000	0.2222	-1.500000	0.0	0.0
0.6540	0.0014	0.0010	1.3735	0.008700	663.	186.8000	1.000	0.2242	-1.000000	0.0	0.0
0.7440	0.0030	0.0021	1.4145	0.007612	1115.	148.8000	1.000	0.2301	-0.500000	0.0	0.0
0.8350	0.0034	0.0024	1.4552	0.004024	1251.	145.6000	1.000	0.2327	0.0	0.0	0.0
0.9270	0.0039	0.0026	1.4722	0.004603	1398.	144.0000	1.000	0.2340	0.0	0.0	0.0

PRINCIPAL BOUNCARY LAYER PARAMETERS FOR
STREAMLINE NO. 9 BOUNDARY DESIGN WITH SUC

X	DT	MT	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2975	0.003736	1710.	342.0000	1.000	0.1518	-0.500000	0.0	0.0
0.0400	0.0013	0.0009	1.4028	0.006714	1099.	337.2000	1.000	0.1529	-1.000000	0.0	0.0
0.0720	0.0013	0.0010	1.3509	0.007595	1104.	328.7998	1.000	0.1548	-1.500000	0.0	0.0
0.1000	0.0014	0.0011	1.3329	0.009089	1120.	318.0000	1.000	0.1574	-2.000000	0.0	0.0
0.1280	0.0015	0.0011	1.3323	0.010492	1138.	305.2000	1.000	0.1607	-2.500000	0.0	0.0
0.1540	0.0016	0.0012	1.3223	0.012409	1146.	290.3999	1.000	0.1647	-3.000000	0.0	0.0
0.1730	0.0017	0.0013	1.3212	0.014703	1169.	276.0000	1.000	0.1690	-3.500000	0.0	0.0
0.1920	0.0018	0.0013	1.3315	0.015475	1183.	264.0000	1.000	0.1728	-3.500000	0.0	0.0
0.2120	0.0019	0.0014	1.3352	0.015852	1198.	251.2000	1.000	0.1771	-3.500000	0.0	0.0
0.2330	0.0021	0.0015	1.3446	0.016596	1221.	238.0000	1.000	0.1820	-3.500000	0.0	0.0
0.2590	0.0022	0.0016	1.3629	0.014801	1252.	224.0000	1.000	0.1876	-3.000000	0.0	0.0
0.2910	0.0024	0.0018	1.3775	0.015345	1275.	209.6000	1.000	0.1939	-3.000000	0.0	0.0
0.3250	0.0026	0.0019	1.3841	0.016407	1281.	196.0000	1.000	0.2005	-3.000000	0.0	0.0
0.3650	0.0028	0.0020	1.3902	0.014941	1304.	184.0000	1.000	0.2010	-2.500000	0.0	0.0
0.4220	0.0028	0.0020	1.3952	0.012835	1223.	173.2000	1.000	0.2133	-2.000000	0.0	0.0
0.4840	0.0029	0.0021	1.3963	0.011112	1199.	163.2000	1.000	0.2198	-1.500000	0.0	0.0
0.5480	0.0031	0.0022	1.4070	0.008024	1197.	156.4000	1.000	0.2245	-1.000000	0.0	0.0
0.6270	0.0031	0.0022	1.4062	0.008708	1181.	150.8000	1.000	0.2286	-1.000000	0.0	0.0
0.7180	0.0032	0.0023	1.4071	0.006437	1183.	146.8000	1.000	0.2317	-0.500000	0.0	0.0
0.8100	0.0036	0.0025	1.4456	0.004690	1313.	144.0000	1.000	0.2339	0.0	0.0	0.0
0.9030	0.0041	0.0028	1.4632	0.004069	1472.	142.0000	1.000	0.2356	0.0	0.0	0.0

PRINCIPAL BOUNDARY LAYER PARAMETERS FOR
STREAMLINE NO. 12 BOUNDARY DESIGN WITH SUC

X	DT	MT	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2975	0.003693	1730.	346.0000	1.000	0.1509	-0.500000	0.0	0.0
0.0390	0.0013	0.0009	1.4006	0.006719	1101.	342.3999	1.000	0.1517	-1.000000	0.0	0.0
0.0710	0.0013	0.0010	1.3269	0.008727	1067.	335.0000	1.000	0.1534	-2.000000	0.0	0.0
0.1000	0.0013	0.0010	1.3076	0.010939	1052.	324.7998	1.000	0.1558	-2.500000	0.0	0.0
0.1250	0.0014	0.0010	1.3188	0.010682	1075.	312.3999	1.000	0.1588	-2.500000	0.0	0.0
0.1510	0.0015	0.0011	1.3071	0.012526	1081.	297.2000	1.000	0.1628	-3.000000	0.0	0.0
0.1700	0.0016	0.0012	1.3033	0.014778	1099.	282.7998	1.000	0.1669	-3.500000	0.0	0.0
0.1880	0.0017	0.0013	1.3115	0.015651	1124.	269.2000	1.000	0.1711	-3.500000	0.0	0.0
0.2080	0.0018	0.0014	1.3204	0.017171	1147.	254.8000	1.000	0.1760	-3.799999	0.0	0.0
0.2290	0.0020	0.0015	1.3335	0.017116	1186.	239.6000	1.000	0.1813	-3.500000	0.0	0.0
0.2550	0.0022	0.0016	1.3578	0.016896	1231.	223.6000	1.000	0.1877	-3.500000	0.0	0.0
0.2870	0.0025	0.0018	1.3817	0.015943	1271.	207.2000	1.000	0.1950	-3.000000	0.0	0.0
0.3220	0.0027	0.0019	1.4095	0.012857	1320.	192.4000	1.000	0.2024	-2.500000	0.0	0.0
0.3620	0.0030	0.0021	1.4312	0.011632	1356.	180.0000	1.000	0.2092	-2.000000	0.0	0.0
0.4210	0.0032	0.0022	1.4432	0.008881	1353.	169.2000	1.000	0.2158	-1.500000	0.0	0.0
0.4840	0.0035	0.0024	1.4536	0.007724	1383.	160.0000	1.000	0.2219	-1.000000	0.0	0.0
0.5480	0.0038	0.0026	1.4800	0.004849	1463.	153.6000	1.000	0.2265	-0.500000	0.0	0.0
0.6290	0.0041	0.0028	1.4729	0.006002	1523.	148.8000	1.000	0.2301	-0.500000	0.0	0.0
0.7210	0.0046	0.0031	1.5015	0.003337	1671.	144.8000	1.000	0.2333	0.0	0.0	0.0
0.8150	0.0052	0.0034	1.5156	0.004130	1841.	142.4000	1.000	0.2352	0.0	0.0	0.0
0.9100	0.0056	0.0037	1.5206	0.003089	1982.	140.8000	1.000	0.2366	0.0	0.0	0.0

PRINCIPAL BOUNDARY LAYER PARAMETERS FOR
STREAMLINE NO. 15 BOUNDARY DESIGN WITH SUC

X	DT	MT	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2975	0.003610	1770.	354.0000	1.000	0.1492	-0.250000	0.0	0.0
0.0370	0.0013	0.0009	1.4110	0.005753	1155.	352.7998	1.000	0.1495	-0.500000	0.0	0.0
0.0680	0.0014	0.0010	1.3654	0.006311	1184.	347.2000	1.000	0.1506	-1.000000	0.0	0.0
0.0940	0.0014	0.0011	1.3421	0.008341	1198.	338.3999	1.000	0.1526	-2.000000	0.0	0.0
0.1110	0.0015	0.0011	1.3393	0.010892	1220.	327.2000	1.000	0.1552	-3.000000	0.0	0.0
0.1360	0.0016	0.0012	1.3348	0.011577	1222.	312.3999	1.000	0.1588	-3.000000	0.0	0.0
0.1540	0.0017	0.0013	1.3412	0.012859	1260.	297.2000	1.000	0.1528	-3.500000	0.0	0.0
0.1710	0.0019	0.0014	1.3435	0.013499	1303.	281.2000	1.000	0.1674	-3.500000	0.0	0.0
0.1900	0.0021	0.0015	1.3732	0.013048	1385.	263.5999	1.000	0.1731	-3.500000	0.0	0.0
0.2110	0.0024	0.0017	1.3920	0.014823	1480.	244.0000	1.000	0.1797	-3.799999	0.0	0.0
0.2370	0.0029	0.0020	1.4378	0.013687	1619.	222.8000	1.000	0.1881	-3.500000	0.0	0.0
0.2710	0.0036	0.0024	1.5070	0.011279	1800.	201.6000	1.000	0.1977	-3.000000	0.0	0.0
0.3070	0.0044	0.0028	1.6010	0.006348	2039.	184.4000	1.000	0.2067	-2.000000	0.0	0.0
0.3490	0.0050	0.0031	1.6290	0.007696	2165.	171.6000	1.000	0.2143	-2.000000	0.0	0.0
0.4110	0.0054	0.0033	1.6394	0.004002	2198.	162.0000	1.000	0.2206	-1.000000	0.0	0.0
0.4760	0.0059	0.0036	1.6205	0.005652	2262.	153.6000	1.000	0.2265	-1.000000	0.0	0.0
0.5430	0.0061	0.0038	1.5993	0.003280	2274.	148.8000	1.000	0.2301	-0.500000	0.0	0.0
0.6260	0.0067	0.0042	1.6037	0.003441	2413.	144.8000	1.000	0.2333	0.0	0.0	0.0
0.7190	0.0072	0.0045	1.5981	0.002193	2567.	142.4000	1.000	0.2352	0.0	0.0	0.0
0.8140	0.0076	0.0049	1.5746	0.003697	2683.	140.4000	1.000	0.2369	0.0	0.0	0.0
0.9100	0.0080	0.0051	1.5662	0.002276	2795.	139.2000	1.000	0.2379	0.0	0.0	0.0

PRINCIPAL BOUNDARY LAYER PARAMETERS FOR
STREAMLINE NO. 18 BOUNDARY DESIGN WITH SUC

X	DT	MT	SF	CF	RDT	U	TURB	RW	VW	SW	CW
0.0	0.0020	0.0009	2.2975	0.003499	1826.	365.2000	1.000	0.1469	0.0	0.0	0.0
0.0300	0.0013	0.0009	1.4076	0.006462	1187.	362.0000	1.000	0.1475	-1.000000	0.0	0.0
0.0550	0.0014	0.0010	1.3812	0.006435	1215.	356.0000	1.000	0.1488	-1.000000	0.0	0.0
0.0790	0.0014	0.0010	1.3680	0.008048	1243.	347.2000	1.000	0.1506	-2.000000	0.0	0.0
0.1020	0.0015	0.0011	1.3564	0.010735	1244.	335.2000	1.000	0.1533	-3.000000	0.0	0.0
0.1180	0.0016	0.0012	1.3484	0.012052	1262.	321.2000	1.000	0.1566	-3.500000	0.0	0.0
0.1350	0.0017	0.0013	1.3611	0.012822	1304.	304.7998	1.000	0.1608	-3.799999	0.0	0.0
0.1520	0.0023	0.0017	1.3921	0.013021	1649.	282.3999	1.000	0.1436	-4.000000	0.0	0.0
0.1720	0.0026	0.0018	1.4534	0.013633	1647.	253.6000	1.000	0.1763	-4.500000	0.0	0.0
0.1990	0.0036	0.0023	1.5753	0.018066	1978.	220.8000	1.000	0.1889	-5.500000	0.0	0.0
0.2340	0.0049	0.0028	1.7456	0.012353	2358.	190.8000	1.000	0.2032	-5.000000	0.0	0.0
0.2730	0.0059	0.0032	1.8709	0.009189	2538.	171.2000	1.000	0.2145	-4.000000	0.0	0.0
0.3840	0.0038	0.0025	1.5478	0.003831	1528.	160.0000	1.000	0.2219	-2.000000	0.0	0.0
0.4490	0.0038	0.0024	1.6176	0.010625	1455.	152.0000	1.000	0.2277	-1.500000	0.0	0.0
0.5180	0.0035	0.0023	1.5026	0.004721	1272.	146.8000	1.000	0.2317	-1.000000	0.0	0.0
0.5780	0.0035	0.0024	1.4548	0.008005	1264.	143.2000	1.000	0.2346	-0.500000	0.0	0.0
0.6730	0.0039	0.0025	1.5270	0.001733	1370.	140.8000	1.000	0.2366	0.0	0.0	0.0
0.7680	0.0043	0.0029	1.5116	0.006390	1500.	138.8000	1.000	0.2383	0.0	0.0	0.0
0.8650	0.0048	0.0031	1.5360	0.001541	1654.	137.6000	1.000	0.2393	0.0	0.0	0.0
0.9620	0.0051	0.0034	1.5079	0.006086	1739.	136.8000	1.000	0.2400	0.0	0.0	0.0

PRINCIPAL BOUNCARY LAYER PARAMETERS FOR
STREAMLINE NO. 21 BCUNCARY DESIGN WITH SUC

X	DT	MT	SF	CF	RDT	U	TURB	RW	VW	SW	GW
0.0	0.0020	0.0009	2.2975	C.C03359	1902.	380.3999	1.000	0.1439	0.0	0.0	0.0
C.0240	0.0014	0.0009	1.4268	0.C04802	1274.	377.2000	1.000	0.1445	0.0	0.0	0.0
0.0460	0.0014	0.0010	1.3866	0.C06000	1304.	372.7998	1.000	0.1454	-1.000000	0.0	0.0
0.0670	0.0014	0.0010	1.3814	C.CC7750	1315.	368.CCCO	1.000	0.1463	-2.000000	0.0	0.0
0.0820	0.0015	0.0011	1.3697	C.CC9554	1315.	360.0000	1.000	0.1480	-2.799999	0.0	0.0
0.0960	0.0015	0.0011	1.3668	0.C10176	1302.	352.0000	1.000	0.1496	-3.250000	0.0	0.0
0.1110	0.C016	0.0012	1.3309	0.026294	1285.	329.0000	1.000	0.1547	-9.000000	0.0	0.0
C.1290	0.0020	0.0015	1.3448	0.C62048	1384.	282.7998	1.000	0.1669	-14.0 *********	0.0	0.0
0.1560	0.0031	0.0022	1.3727	0.C95320	1649.	214.8CCO	1.000	0.1915	-16.5 *********	0.0	0.0
0.1760	0.0039	0.0025	1.5988	0.C37393	1871.	191.COCO	1.000	0.2035	-9.500000	0.0	0.0
0.1970	0.C050	0.0026	1.8871	0.012894	2066.	165.60CO	1.000	0.2182	-9.450000	0.0	0.0
0.2150	0.0036	0.0027	1.3277	0.C93739	1424.	159.0000	1.000	0.2226	-4.250000	0.0	0.0
0.2410	0.0232	0.0000	0.CCCC	C.C00000	8717.	150.0CCO	1.000	0.2292	0.0	0.0	0.0

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